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TIMERS FOR ORDNANCE SYMPOSIUM

FLUTTER ARMING AND TIMING MECHANISM FOR FUZES

UNITED STATES NAVAL ORDNANCE LABORATORY
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23

FLUTTER ARMING AND TIMING MECHANISM FOR FUZES

by

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ABSTRACT: The components in the conventional mechanical fuzing system for bombs include an arming vane to extract energy from the environment, high speed bearings to ensure proper rotational characteristics of the arming vanes, clutch or similar mechanism to sense a specific velocity threshold and a clock escapement or governor for proper delay arming of the fuze. This ~~paper~~ report is concerned with another mechanism that current exploratory development shows promise of accomplishing the same ends. The mechanism has the potential to become an inexpensive environmentally operated delay device that could effect a considerable savings if used on fin stabilized cluster bomblets.

The operational basis of this arming mechanism is a controlled flutter phenomenon. A rectangular flat-plate oscillating member is pivoted about its midchord and has a spring member providing a restoring moment. Placed edgewise in a wind stream, the system is in unstable-stable equilibrium; at a predetermined air speed or above, aerodynamic lift on the flat plate overcomes the restoring moment and the oscillator vibrates.

Vibrations occur at the natural frequency of the oscillator-restoring member combination, thus replacing the mechanical clockwork escapement as a time base. Power from the vibrating oscillator drives a series of gears through a pawl and ratchet mechanism to align an explosive train. High speed bearings are eliminated.

Wind tunnel and other data are presented which indicate the feasibility and characteristics of the foregoing system.

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INTRODUCTION

This operating principle for bomb fuzes came about through an observation of traffic signs vibrating in a strong wind about the single pole support. Although the geometry was not important to the movement of the sign the relative position to the wind direction and the magnitude of the wind was. When gusts of wind forced the signs to vibrate it was noted that a certain regularity or frequency was apparent.

With these observations in mind the fuze designer deduced the following:

a. A flat plate directed edgewise into an air stream environment is a source of potential energy that can be applied to fuze design.

b. The flat plate will vibrate or oscillate about a fixed axis with a regularity that is a function of its mass and stiffness, thus providing a time base.

c. The flat plate will oscillate only when the wind velocity has reached a critical speed, thus a threshold safety is possible.

Looking at the vibrating flat plate from a broader aspect this phenomena is not unique to our case. In the mid-thirties some aircraft were losing tail and wind sections due to a similar type of vibration mode. This was brought about primarily by the aircraft speeds that have progressively increased. The destructive consequence of dynamic instability is known to the aerodynamic engineer as "flutter".

In flight, the aerodynamic forces causing vibration can lead to three basic types of vibration. If a wing has the ability to vibrate like a simple beam (flexure) as well as torsionally, an unstable divergent motion can result. Lift in a torsional mode of vibration is dependent on the twist of the wing section. The greater the angle of twist (or angle of attack of the wing to the air stream) the wing goes through from a static position, the greater the magnitude of the aerodynamic lift forces become. When the wing displacement of the flexual vibration is in phase with the lift forces of the torsional vibration, the amplitude of the motion increases on succeeding cycles. When this unstable divergent motion is encountered, the increase in amplitude will continue until failure of the wing section results. This type of motion, "true flutter", is indicated by Figure 1.a.

If the wing tip of an aircraft is deflected and starts to vibrate but internal and external damping is present, the motion will gradually cease in a finite time. This type of motion will allow the displaced member to return to its original position is a stable type of damped motion indicated by Figure 1.b.

A third type of vibration is the unstable oscillating type as indicated by Figure 1.c. The wing tip deflected will continue to vibrate indefinitely with no change in amplitude. This is a controlled condition of the flutter motion.

FUZE OPERATION:

The type of vibration that we are seeking in the fuze would be of the latter type, the "controlled flutter". When the motion starts the amplitude should remain relatively constant along with the frequency. The constant amplitude is needed for a regulated power take-off system to align an explosive train. The constant frequency is needed to insure specific time delay for arming. The controlled flutter motion can be achieved by using a rigid flat plate (no flexure) and relying only on the torsional mode for a restoring force.

A rectangular flat plate is semi-enclosed and pivoted about an axis through its midchord. The midchord location was selected to obtain a statically balanced oscillator. In this set up the flat plate would be free to rotate like a propeller if some disturbing force was imposed on the plate. However, a restraining member in the form of a torsion bar is fixed to the pivot axis. This not only gives rigidity to the flat plate but will bias the flat plate to a specific static orientation with the air stream. The relative position of the air stream and the flat plate is shown in the simplified sketch in Figure 11.a. Applying a strong enough air stream perpendicular to the pivot axis and the leading edge of the flat plate, a vibration will start provided a dead center condition does not exist.

When the vibration begins, frequency and amplitude assumed constant, power must be extracted from the flat plate or oscillator and somehow align an explosive train. Of the many ways for using the oscillator energy the pawl and ratchet system appear to work best. A spring-loaded indexing finger is located on the pivot axis of the oscillator. If the oscillator is already deflected to the outboard position or approximately +15 degrees from the biased static position, the indexing finger will catch one tooth of the ratchet wheel. The oscillator will rotate ½ of a cycle or to a position of approximately -15 degrees from the biased static position and turn the ratchet wheel a specific number of degrees. The amount of rotation of the ratchet wheel per cycle of the oscillator is determined by the physical size and number of teeth on the ratchet wheel along with the amplitude of vibration of the oscillator. A pawl now engages the ratchet wheel to ensure a locked unidirectional motion of the ratchet. The last half of the oscillator cycle drags the index finger back over the ratchet wheel. As the oscillator reaches its maximum amplitude (+15 degrees) to start another cycle, the index finger is ready to re-engage the ratchet wheel. Oscillatory motion is thus transferred to intermittent circular motion and useful work.

On the ratchet wheel shaft is a pinion gear that will drive a wheel or series of pinions and wheels. Time delay can be built into the number of gears cascaded.

Figure III shows the first workable version that uses the controlled flutter motion. It will hereafter be referred to as the flutter arming mechanism (FAM). The restoring member Figure III.a is nothing more than a piece of music wire. The oscillator shaft (pivot axis) fits through and locks onto the oscillator. The oscillator is statically balanced about the pivot axis. The indexing finger is also a piece of music wire that is fastened to the oscillator shaft but not rigidly. The locking pawl is flat wire that can be adjusted to apply a light drag on the ratchet as necessary for proper operation. The last set of gears on this mechanism consists of a driving pin and geneva output wheel. This type of drive motion reduces the amount of gears necessary for the time delay. The gears are to be punched from standard stock, the shafts made by screw machine and the wire cut from standard stock.

The stab initiated detonator will be located in the enlarged hub of the geneva wheel. After a fixed time delay (once the oscillator has started to vibrate) the detonator will be rotated 90° to an armed position in line with stab firing pin.

The restoring member, indexing finger, pawl, and gears are to be located in the fuze body, Figure III.b, which is formed for ogival mounting. It is necessary to shield the gear train from the high ram pressure of the air stream. In a previous test model the air stream was found to be driving the exposed gears independent of the oscillator movement. The body shown in Figure III.b is a closely machined experimental prototype. The finalized fuze body will be similar to this but will be a zinc or aluminum die casting.

The oscillator shown in Figure III.b is to be a stamped flat plate, blunt leading edge with a trapezoidal surface area. This area configuration lends itself nicely to the fuze configuration for this particular application.

The fuze body is held to the housing Figure III.c which in turn is fastened to the ogive of the bomb. The air enters the housing at the leading edge of the oscillator. The housing shows a channeled flow device just prior to the oscillator. The first wind tunnel test did not have this addition but the reasons why it was included will be covered later in this report. After the air passes over the oscillator it will exit out the back of the housing into the free stream air.

The oscillator and geneva wheel movements can be observed through the viewer windows in the housing. In wind tunnel tests these ports are covered with a thin plexiglass sheet. The actual fuze will have but one rotor inspection viewer to determine the safe or armed status.

SYMBOLS

I = moment of inertia of oscillator (in-lb-sec^2)

C = oscillator damping coefficient

K = wire spring constant $\left(\frac{\text{lb-in}}{\text{Rad.}}\right)$

M = aerodynamic moment

L = aerodynamic lift

α = angle of attack; angle between oscillator and free stream air

a.c.= aerodynamic center for aerodynamic forces on oscillator

$\bar{a}$ = distance from pivot axis to aerodynamic center (ft)

C_N = lift coefficient; depends on configuration

ρ = density of air

U = air stream velocity (ft/sec)

U_{CR} = air stream velocity at threshold for non-channeled flow (ft/sec)

U'_{CR} = air stream velocity at threshold for channeled flow (ft/sec)

S = surface area of oscillator (ft^2)

E_W = modulus of elasticity for restoring member (lb/in^2)

I_W = moment of inertia of wire (in^4)

ℓ = length between supports of restoring member (ft)

ω = natural frequency of oscillator - wire combination (C.P.S.)

A_b = area of nozzle at "b" location (ft^2)

A_d = area of nozzle at "d" location (ft^2)

THEORY

A clear-cut mathematical explanation of the starting and sustained motion has not been formalized. Work on this is presently being done with the aid of specialists in the field of aeroelasticity. Various theories have been proposed but experimental results do not agree with any one mathmatical expression. Future designs and definition of physical limitations of this motion will necessitate the exact solution.

Of the theories that can be generated from this phenomenon a basic approach would seem in order. The general differential equation of motion for the single degree of freedom problem of the oscillator in a two dimensional, incompressible free air flow reads

$$I\ddot{\vartheta} + C\dot{\vartheta} + K\vartheta = M \qquad \text{Eq. 1}$$

This equation is valid only for free stream considerations and will have to be corrected if channeled air flow to the oscillator was considered.

The original theory of how the FAM worked was thought to be a relatively simple problem of dynamics. An air stream impinging the leading edge will give an aerodynamic lift to the oscillator. The lift is a high-low pressure difference on each face of the oscillator and is a function of the angle of attack and the magnitude of the air stream velocity. If the oscillator is directed into the air stream, with no incidence, no motion will result. The lift on both sides of the oscillator are completely negated. The oscillator is in unstable-stable equilibrium regardless of the magnitude of the air stream. But, two factors are in our favor: (1) the bomb will have a pitch and yaw associated with its travel to a target that will not allow a sustained perfect zero angle of attack with the air stream, and (2) the irregularities at manufacture and assembly will automatically bias the oscillator thus producing a finite angle of attack. The resultant pressure distribution can be considered to act through a common point on the surface of the oscillator called its aerodynamic center (a.c.) giving rise to an aerodynamic moment or pitching moment about its pivot axis. For a rectangular flat plate this a.c. is located at a distance of one-quarter chord distance from the leading edge. The a.c. for a trapezoidal shaped flat plate is approximately one-quarter of the surface area from the leading edge. The oscillator will not move from its biased position until the aerodynamic moment is large enough to overcome the torsional resisting moment.

The aerodynamic moment will deflect the oscillator approximately 15° to a point where stalling occurs. This is analogous to a stall condition inherent to airplanes.

At a stall condition the lift on the oscillator has significantly decreased allowing the restoring moment to be unbalanced. The oscillator is then forced to the neutral position but "overshoots" slightly. The "overshoot" is due primarily to the inertia of the oscillator. The lift forces are again created on the reverse face and the cycle repeats. For a given oscillator the threshold velocity or critical speed (U_{CR}) could be changed simply by using a stronger or weaker restoring member, i.e. change the diameter or free length of the music wire.

For this simplified theory the free vibration damping coefficient C was neglected and the aerodynamic moment M was assumed a function of the angle of attack and magnitude of the air stream. The torsional spring constant was assumed linear and a function of ϕ only.

With C = 0 $\quad M = f(\phi, U)$ equation (1) becomes

$$I\ddot{\phi} + K\phi = M \qquad \text{Eq. 2}$$

$$M = L \cdot \bar{a} \text{ where } L = C_N \tfrac{1}{2}\rho U^2 S$$

$$C_N = 2\pi\phi \text{ for a flat plate}$$

$$M = \pi \rho U^2 S \cdot \bar{a} \phi$$

$$K = \frac{12 E_W I_W}{\ell}$$

For small angles the threshold velocity U_{CR} would be

$$K\phi = M$$

$$K = \pi \rho U_{CR}^2 S \bar{a} \qquad \text{Eq. 3}$$

$$U_{CR} = \left[\frac{K}{\pi\rho S \bar{a}}\right]^{\frac{1}{2}}$$

The threshold velocity is defined as the lowest speed that a structure will exhibit sustained harmonic oscillations at given air densities and temperatures.

With the standard blunt oscillators in free air the expected threshold velocities as a function of wire spring constant are plotted in Figure IV.a.

At or just above the threshold velocity the frequency of vibration for this basic theory is the systems natural frequency. The system refers to the oscillator-torsion spring combination. From equation (2).

$$\omega = \left[\frac{K}{I}\right]^{\frac{1}{2}} \qquad \text{Eq. 4}$$

For the standard oscillator the natural frequencies vs spring constant are plotted in Figure IV.b.

Since the FAM was intended to compare with the conventional fuze, it should meet all their requirements. The arming vanes, bearings and clutch work in the present fuzing will sense a threshold velocity of 170 ± 10 knots at any reasonable angle of attack with the air stream. Since the oscillator is to replace all these parts, it should sense the same velocity threshold before vibrating. The oscillator also has to meet the requirement of vibrating at constant frequency to replace the mechanical clock type escapement. Tests were so conducted.

WIND TUNNEL

Set-Up: The fuze shown in Figure III was mounted on an ogive to simulate the frontal configuration of the bomb. This in turn was mounted on a sting and fastened to the rotating arm in supersonic wind tunnel #1 at NOL(WO). The rotating arm can turn to give from -6° to $+20^{\circ}$ angle of attack of the air stream to the oscillator. The sting is nothing more than a steel support about 14 inches long that holds the fuze in the center of the tunnel test section regardless of the angle of attack.

Instrumentation: Two Electro #3055A magnetic transducers were located in the ogive to sense the frequency of the oscillator and the output motion of the geneva wheel. Trouble was encountered in recording the geneva wheel movement so consequently instrumenting this phase was dropped. The output of the remaining magnetic pick-up for the oscillator movement was put through an amplifier to both an X-Y plotter and a DARE recorder (digital analog recording equipment). The plotter gave on the spot functioning data but the tapes needed to be processed before its more accurate information could be used. Both outputs were set up to give frequency as a function of time and angle of attack but only the tape recorded Mach number, static pressure and Reynolds number.

Parameters: The spring constants were changed to obtain a study of the threshold velocities and frequencies. The diameters of the music wire tested were .007 and .010. A piece of flat spring stock .005 by .055 was also tested. The leading edge of the oscillator will influence the functioning characteristics so blunt, concave and round frontal configurations were tried. See Figure II.b for frontal configurations and oscillator dimensions used on these wind tunnel tests. Some tests were with 0 angle of attack and some a sweeping angle of attack from -6° to $+20^{\circ}$.

RESULTS - WIND TUNNEL TESTS

a. Figure V is a plot of the actual frequency attained as a function of time. The air speed was varied on different runs to determine the actual threshold velocity. With a blunt frontal configuration for the oscillator in non-channeled flow and using a .010 diameter restoring wire the threshold velocity was 138 knots. These tests were for an oscillator of 0° angle of attack. The calculated threshold velocity of 140 knots compares almost exactly with the experimental velocity.

The frequency of vibration did not function as planned. At the threshold velocity the oscillator started to vibrate at 34 cps and as the air stream velocity increased the frequency increased to 65 cps at 400 knots. The natural frequency for this system was calculated at 51 cps.

b. The parameters shown in Figure VI are the same as those in Figure V except for the angle of attack. In Figure VI the runs were started at -6 degrees angle of attack, rotated through 0 degrees until +20° was reached. The threshold velocity dropped slightly to 125 knots at 12° angle of attack. A sustained vibration started at a speed of 127 knots. From this family of curves it is evident that the higher angles of attack are lowering the threshold velocities and driving the frequencies higher. At the higher velocities (481 knots) the frequencies changes from 67 cps at -4° to 85 cps at +20°. The frequency difference at the threshold velocity at zero degrees and +20° degrees is 8 cps.

At -3° there appears to be a point of inflection for the curves. This indicates the true zero angle of attack should be at -3° for this series of tests. Assembling the fuze probably caused a slight misalignment.

The frequencies at zero degrees in Figure VI compare closely with those in Figure V.

c. The frontal configuration of the oscillator was changed from blunt to concave to determine any change in functioning characteristics (Figure VII). The angle of attack was swept through -6° to +20°. The flow was not channeled and the wire was .010 diameter, the same size used for the runs in Figures V and VI. The threshold velocity is approximately 120 knots as compared to 140 knots calculated.

Three noticeable differences in Figure VII from Figure VI are: (1) the starting frequency is the natural frequency of the system 51 cps, (2) the frequency is driven upward by the air stream but not as much as with the blunt oscillator and (3) the frequency of 20° is within 5 cps of the frequency at 0° angle of attack for each run.

For the limits of the velocity range the frequency for this configuration is 61 ± 10 cps or ± 16.5%.

d. The frequency of vibration for a blunt oscillator with a .007 diameter restoring wire as a function of the angle of attack for non-channeled flow is shown in Figure VIII. The calculated threshold velocity and natural frequency of this system are 85 knots and 31 cps respectfully. The experimental threshold velocity was found to be 110 knots and the system did start to vibrate at the natural frequency. At 0° the frequencies were 32 cps at threshold to 50 cps at 514 knots. At the higher angles of attack, 20°, the frequency goes from 32 cps at threshold to 59 cps at 514 knots. For the velocity range tested this would give an effective frequency of 46 ± 13 cps.

The results up to now were for a free stream unrestricted flow. Tests were conducted with a restricted or channeled flow member placed in front of the oscillator in an attempt to keep the frequency relatively constant at high angles of attack. Note figures VI and VIII. The channeling effect will direct the air flow to the leading edge rather than impinging on the side surface area of the oscillator.

Figure IX shows configuration of the channeling used. The channeling size chosen is not necessarily optimum but limited conclusions can be drawn from this set-up.

The air flow that the oscillator will witness will be different in magnitude than the actual air flow due to the nozzling effect of the channel. The calculated threshold velocity for the channeled flow will be lower than the free stream threshold velocity. The equation of continuity will be used since we are assuming steady, incompressible flow.

$$d(AU) = 0 \quad \text{Eq. of Continuity} \qquad \text{Eq. 5}$$

$$\text{or } A_1U_1 = A_2U_2$$

Using the width, See Figure IX, as the characteristic dimension and equations 3 and 5 the threshold velocity (U^1_{CR}) for channeled flow will read

$$U^1_{CR} = \frac{d}{b}\left[\frac{K}{\pi\rho\ S}\ \frac{-}{a}\right]^{1/2} \qquad \text{Eq. 6}$$

The b dimension can be obtained by direct measurement but the d dimension is rather difficult to ascertain. The flow in the center of the channel will differ somewhat from the flow at the extremities of the stream tube. Assuming a 75% diffused flow from the velocity at entrance to the nozzle, the ratio

$$\frac{d}{b} = .75$$

therefore equation 6 will read

$$U^1_{CR} = .75\left[\frac{K}{\pi\rho\ S}\ \frac{-}{a}\right]^{\frac{1}{2}} = .75\left[U_{CR}\right]^{\frac{1}{2}} \qquad \text{Eq. 7}$$

The natural frequency of the channeled flow will not differ from that of the non-channeled flow.

The runs in Figure IX are for a rounded leading edge on the oscillator with a flat wire restoring member .055 by .005. The threshold velocity U^1_{CR} calculated is 113 knots compared to 123 knots obtained experimentally.

The frequency at the higher angles of attack (+20°) does not diverge as it did with the non-channeled flow. However, some divergence at 10° with a 300 knot air speed is noticed. Runs at a a higher velocity than 300 knots were not taken. The natural frequency for this series of tests is 55 cps.

VIBRATION TEST

One important question that has been asked about this fuzing principle since it was first conceived has been the effect of vibration. Will aircraft and other transport vibration modes affect the oscillator, ratchet and gearing arrangement such as to arm the fuze in transit?

The oscillator is a balanced mass pivoted about its center of gravity. No inertia effects will cause rotation due to the equal mass distribution but it is possible that there is a resonant frequency.

The fuze shown in Figure III was subjected to a severe aircraft vibration test (MBR-HFV). The test consisted of placing the fuze in three different positions with a .15" peak-to-peak amplitude, a 5g loading, and a frequency range from 10 to 2,000 cps. A synchronized strobe was used to observe any resonant frequencies and the results are observed findings.

The first position placed the plane of the oscillator horizontal with the bed of the vibration table. A resonant frequency at 670 cps was observed. The oscillator was vibrating constantly but the ratchet wheel was vibrating in a random manner. Above and below this resonant frequency (10 to 2,000cps) no other observable vibration appeared.

The second position placed the plane of the oscillator and the pivot axis vertical. A resonant frequency of 1100 cps was noted. The oscillator vibration was constant and the ratchet wheel would index a few degrees, stop momentarily then start again.

The third position placed the oscillator vertical with the pivot axis horizontal. A resonant frequency at 1740 cps was noted with the same results as in position 2. This particular test was carried above 2,000 cps to 2,330 cps where another resonant frequency was observed.

At all resonant frequencies the oscillator was stopped from vibrating by placing a finger on its leading edge. The ratchet wheel still moved in a random manner.

Since this vibration test has been conducted, a bias spring on the ratchet wheel has been added in an attempt to eliminate this problem. Additional tests will have to be conducted to insure this spring will work as planned.

CONCLUSION

Before any conclusions are drawn from the tests reported on the FAM as an S&A mechanism bear in mind that only one physically defined oscillator was tested. Although three leading edge configurations for the oscillator were tried, the pivot axis remained the same in all three cases. A different axis location **fore or aft** of the center of gravity could significantly change the functioning characteristics.

This indicates the importance of obtaining a concise mathematical expression that will predict the functioning when either one or more parameters are changed. The tests conducted were limited in number but they will serve as a guide for present explanation and future exploration of this arming principle.

1. The wind tunnel results of the F.A.M. indicate that it is possible to obtain a predictable velocity range for operation. The calculated value of the critical velocity for unchannedled flow is within experimental accuracy.

2. For all the tests except one, the frequency of vibration at start-up was the natural frequency of the oscillator-restoring member combination.

3. The one exception points out the possibility of singularities existing between the aerodynamic moment, the physical size of the oscillator and the resisting torque.

4. The frequency of vibration is not constant with air stream velocity. The vibration frequency is forced in a direct proportion to the magnitude of the air stream velocity. Aerodynamic factors not included in the basic theory are influencing the frequency response.

5. The aerodynamic moment is more likely a function of $\ddot{\vartheta}$, $\dot{\vartheta}$, ϑ and U. With system damping ($C \neq 0$) the frequency after threshold should be replaced by a damped natural frequency.

6. The frequency of vibration at all reasonable air speeds for the FAM does not appear too precise. However, the delay arming accuracy needed for an S&A device does not require a high degree of precision.

7. In the free stream unchanneled flow the concave oscillator gave more constant frequency response at all air speeds and angles of attack than the blunt oscillator.

8. The effect of the channeled flow is not conclusive but tentative results indicate that the frequency is held more constant at all angles of attack.

9. The first approximation for the cost of the FAM in pilot production can be estimated by the number of component parts. Comparing this total with the number of parts comprising a typical bomblet fuze and using a production factor the cost reduction per fuze coula be approximately 60 to 75%.

10. The results of the exploratory development to date indicate the feasibility of this simple, inexpensive, environmentally operated device as an S&A mechanism.

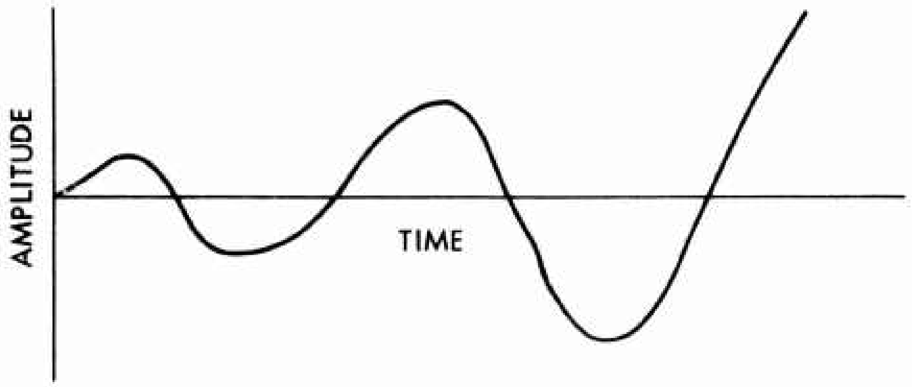

FIG. 1 (a) UNSTABLE DIVERGENT MOTION "TRUE FLUTTER"

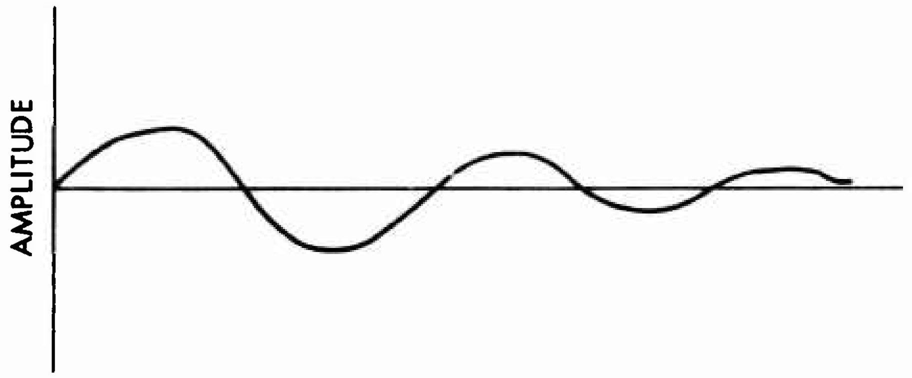

FIG. 1 (b) DAMPED MOTION

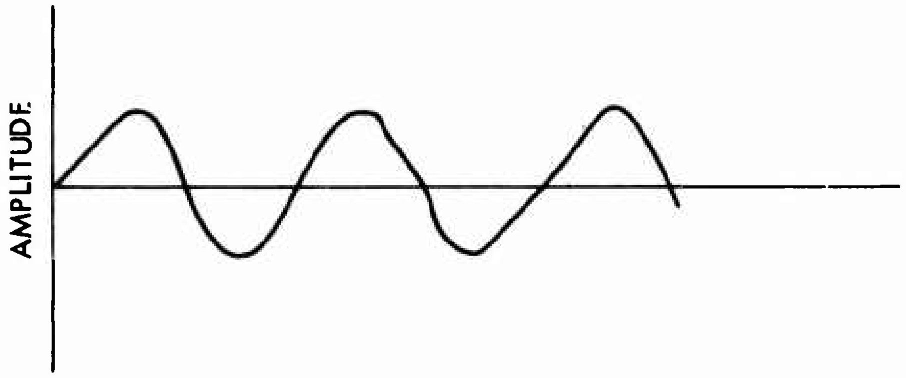

FIG. 1 (c) UNSTABLE OSCILLATING MOTION "CONTROLLED FLUTTER"

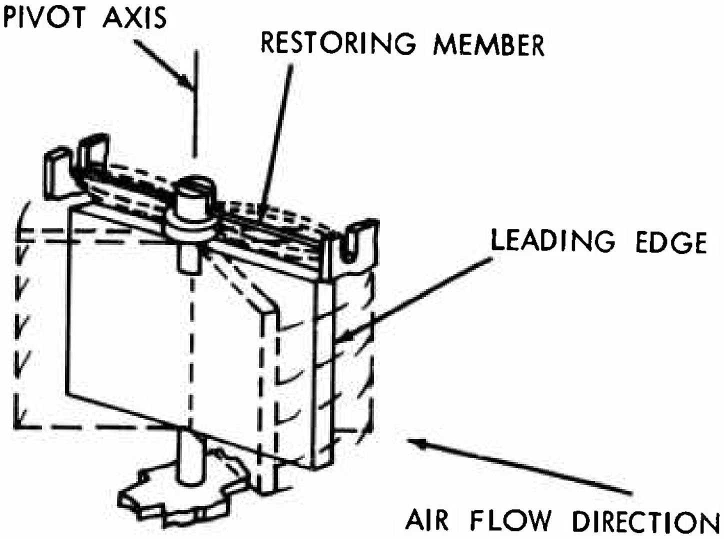

FIG. II (a) OSCILLATOR BIASED POSITION

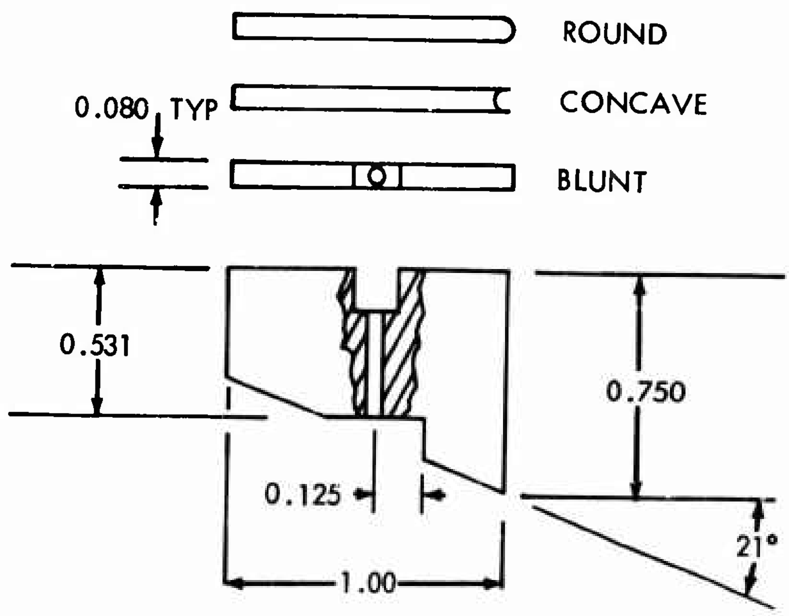

FIG. II (b) OSCILLATOR CONFIGURATION

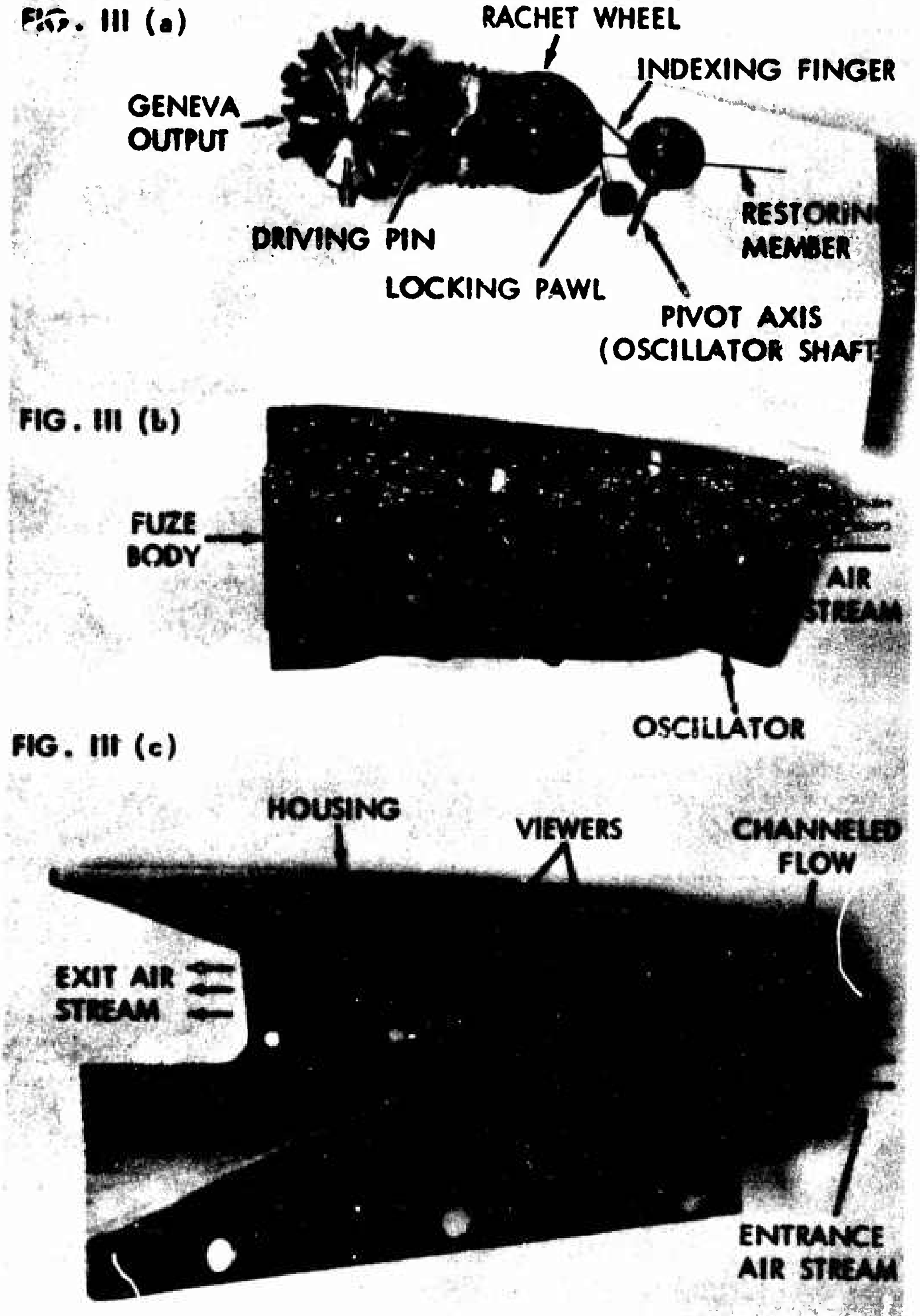

FIG. III FLUTTER ARMING MECHANISM

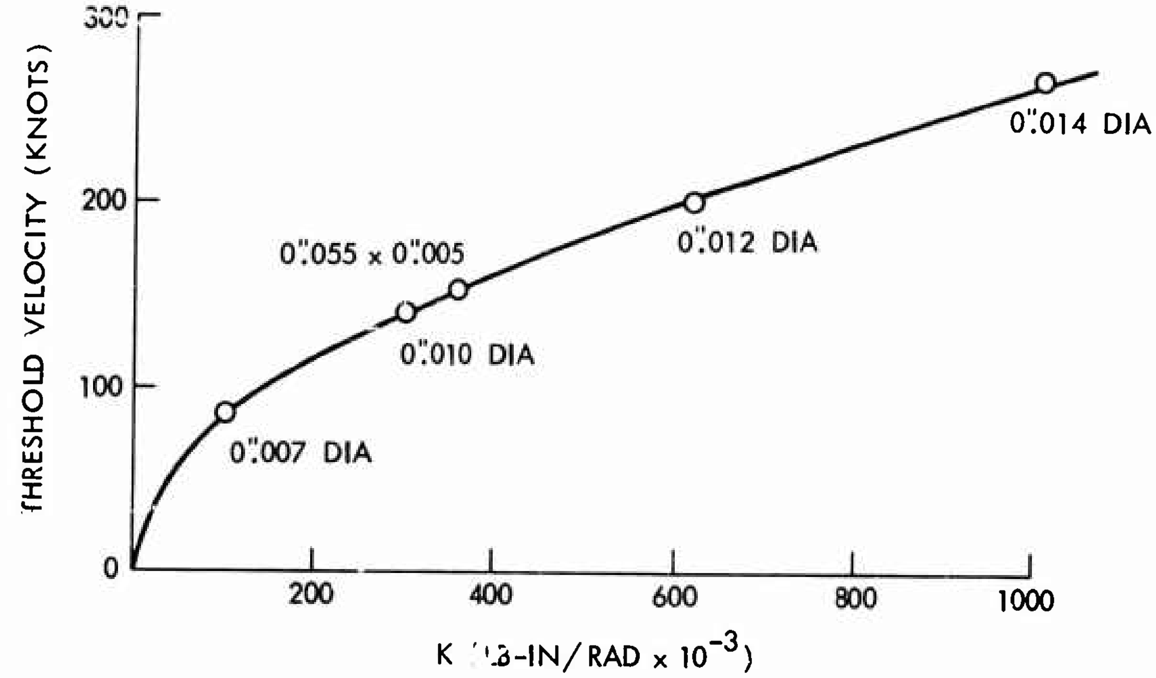

FIG. IV (a) THRESHOLD VELOCITY VS SPRING RATE

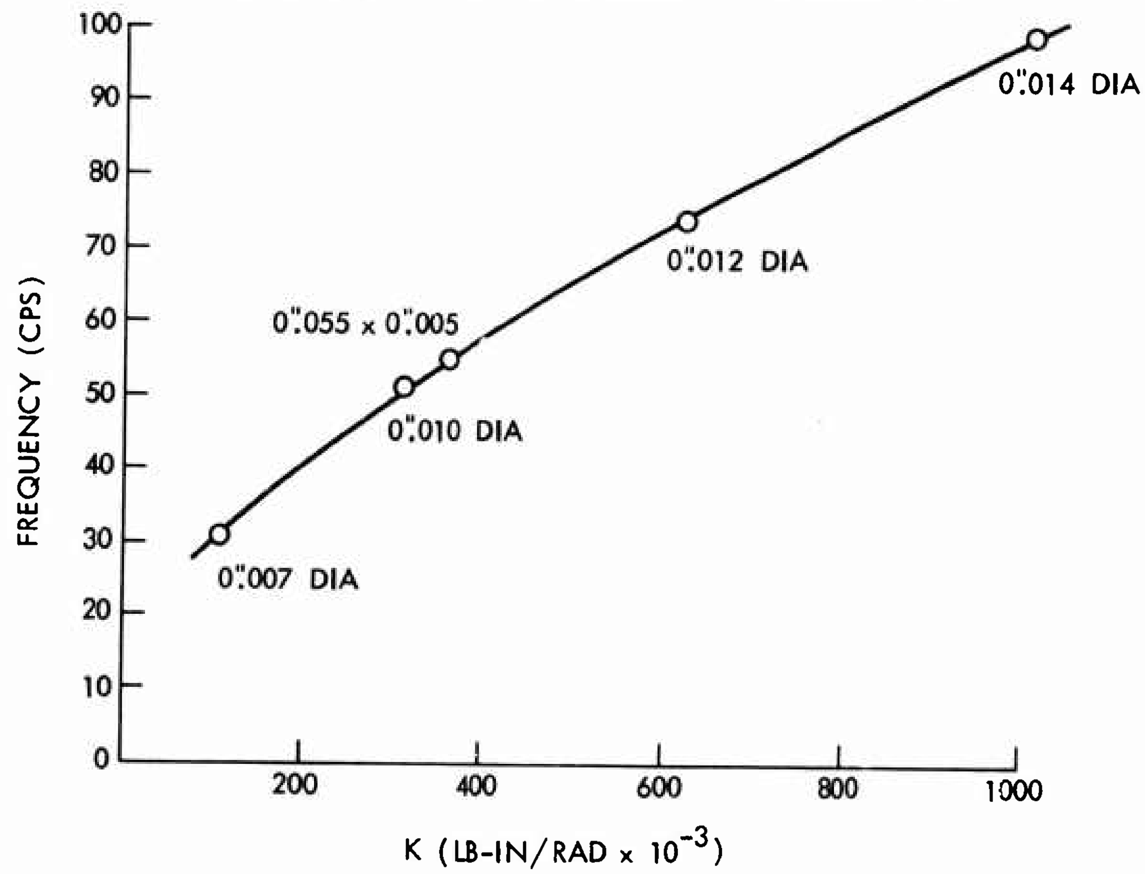

FIG. IV (b) FREQUENCY VS SPRING CONSTANT

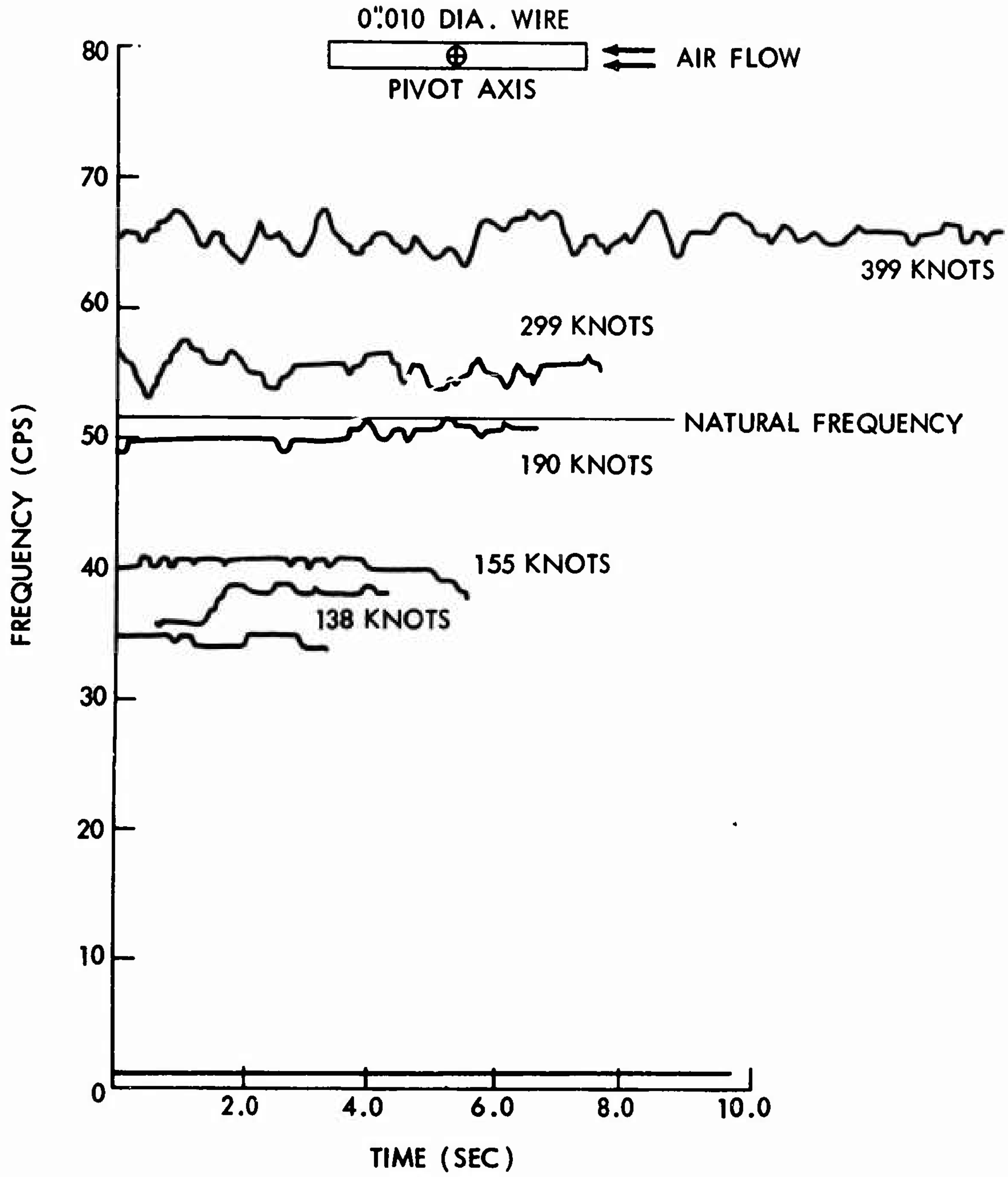

FIG. V VIBRATION FREQUENCY VS TIME FOR BLUNT OSCILLATOR IN FREE STREAM AIR

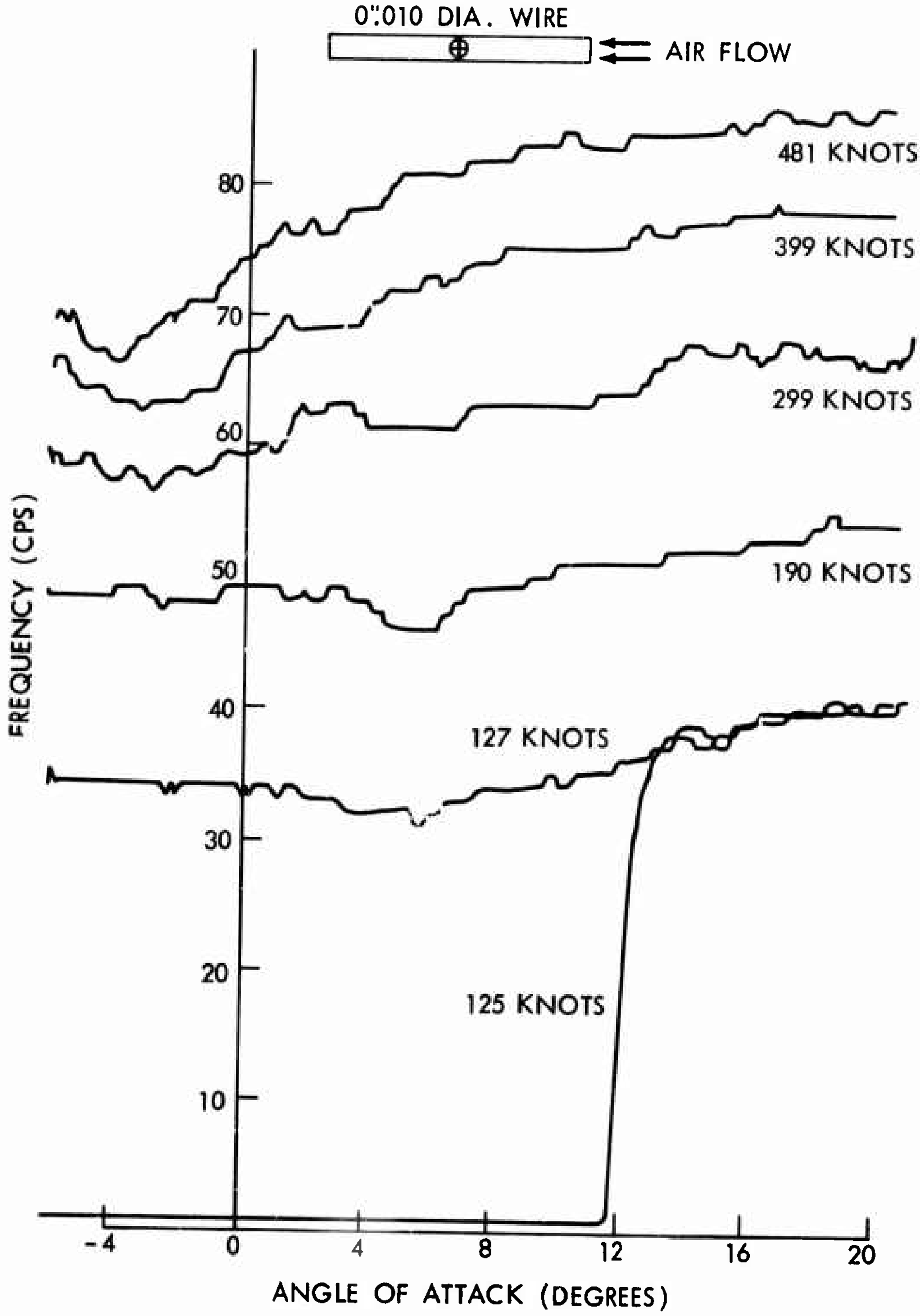

FIG. VI VIBRATION FREQUENCY VS ANGLE OF ATTACK FOR BLUNT OSCILLATOR IN FREE STREAM AIR

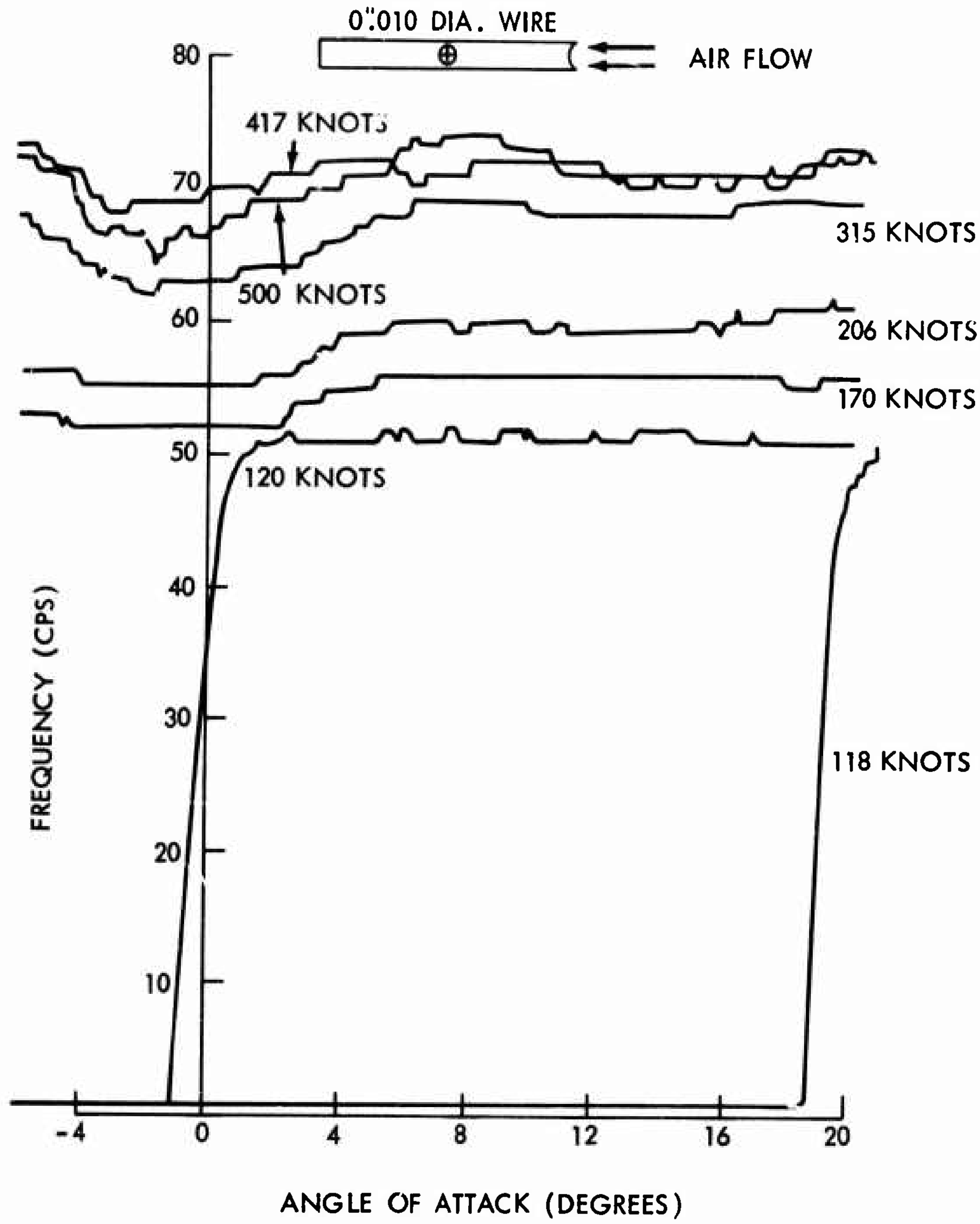

FIG. VII VIBRATION FREQUENCY VS ANGLE OF ATTACK FOR CONCAVE OSCILLATOR IN FREE STREAM AIR

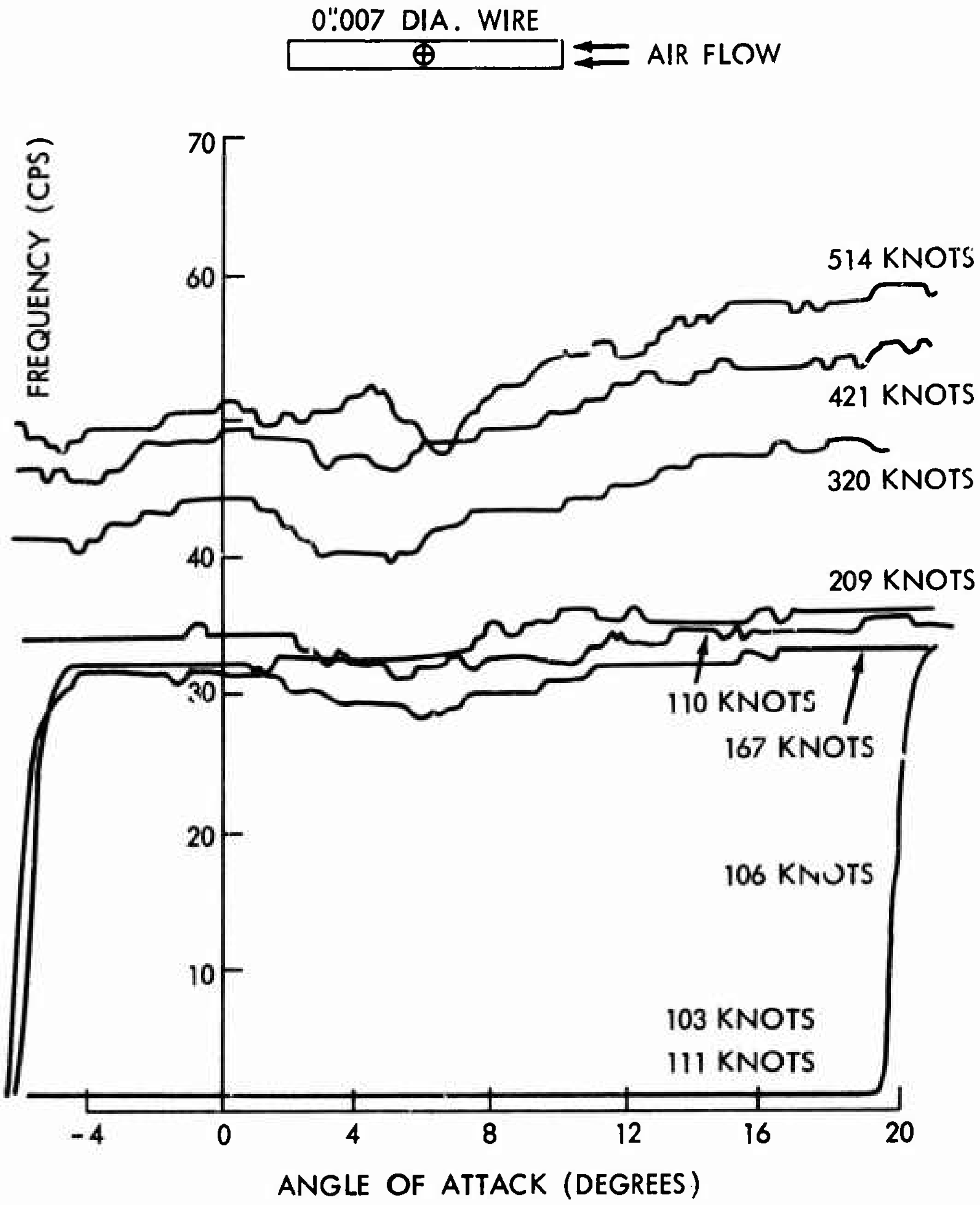

FIG. VIII FREQUENCY VS ANGLE OF ATTACK FOR BLUNT OSCILLATOR IN FREE STREAM AIR

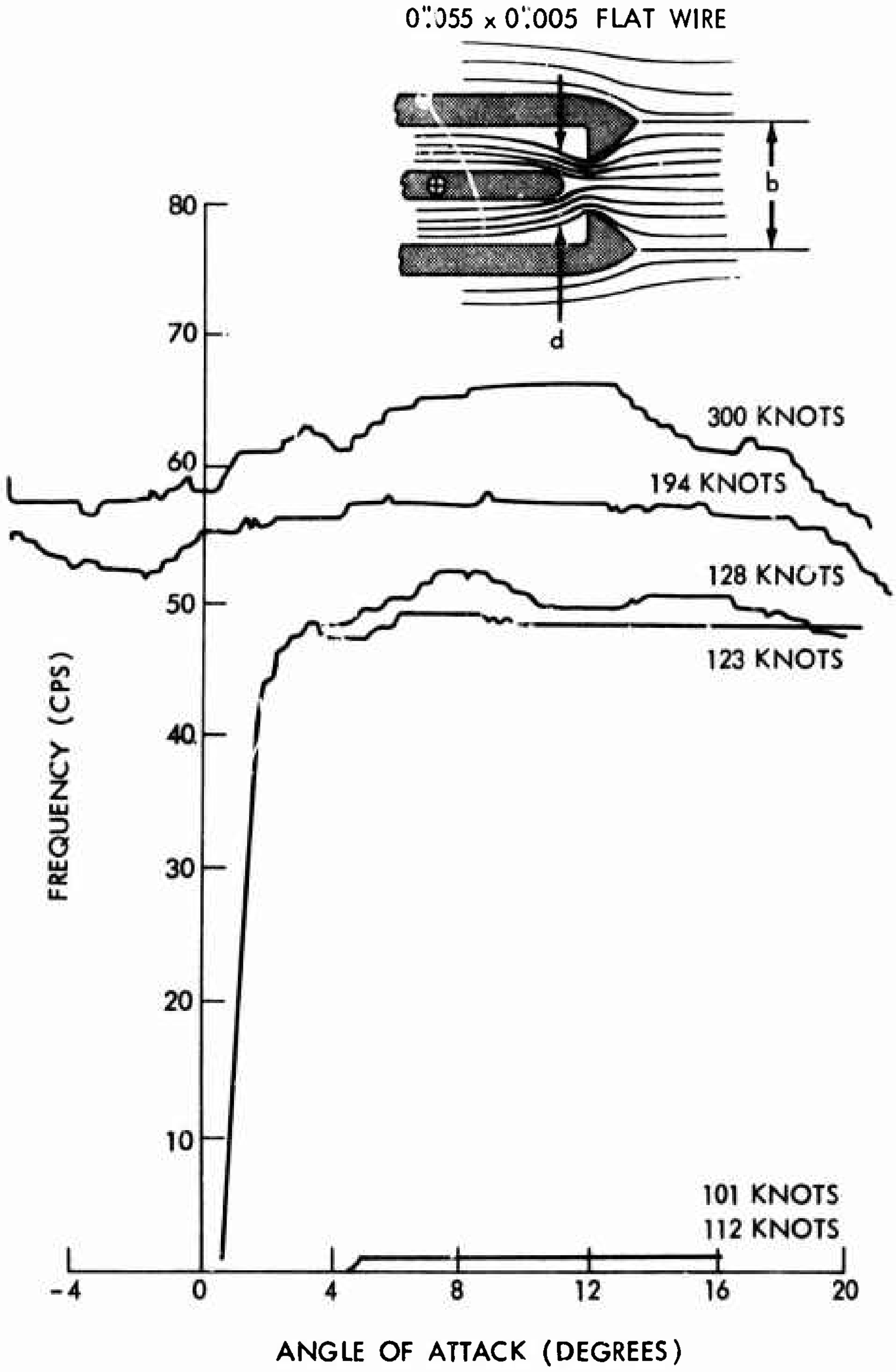

FIG. IX FREQUENCY VS ANGLE OF ATTACK FOR ROUND OSCILLATOR IN CHANNELED FLOW

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